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RESEARCH ARTICLE

Estimating natural landscape changes from 1992 to 2030 in the conterminous US

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Abstract Quantifying landscape dynamics is a central goal of landscape ecology, and numerous metrics have been developed to measure the influence of human activities on natural landscapes. Composite scores that characterize human modifications to landscapes have gained widespread use. A parsimonious alternative is to estimate the proportion of a cover type (i.e. natural) within a spatial neighborhood to characterize both compositional and structural aspects of natural landscapes. Here I extend this approach into a multi-scale, integrated metric and apply it to national datasets on land cover, housing density, road existence, and highway traffic volume to measure the dynamics of natural landscapes in the conterminous US. Roughly one-third of the conterminous US (2.6 million km^2) in 1992 was classified as human-dominated. By 2001 this expanded by 80,800 km^2, and forecasted residential growth by 2030 will potentially lead to an additional loss of up to 92,200 km^2. Wetland cover types were particularly affected. The natural landscapes metric developed here provides a simple, robust measure of landscape dynamics that has a direct physical interpretation related to proportion of natural habitat affected at a location, represents landscapes as a gradient of conditions rather predicated on patch/matrix definition, and measures the spatial context of natural areas.

Keywords Natural landscapes · Landscape dynamics · Human modification · Land use change · Road use

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Introduction

Increasingly, land resource managers are concerned about the influence of human activities on ecological patterns and processes and their effects on long-term conservation of biodiversity (Foley et al. 2005; Crooks and Sanjayan 2006; Hilty et al. 2006; Hansen and DeFries 2007). For example, understanding the landscape dynamics in and near parks is a top priority for the US National Park Service and Forest Service (GAO 1994; Bosworth 2004; Fancy et al. 2008; Gross et al. 2009; Svancara et al. 2009; Wade and Theobald 2010). Landscape ecologists and conservation scientists have developed a variety of measures of the influence of human activities on natural landscapes, typically by characterizing three primary aspects of landscape pattern: composition, structure, and function (Noss 1990). Various landscape metrics have been compared in a number of review papers (e.g.,

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Gardner et al. 1987; Gustafson 1998; Turner 2005; Kindlmann and Burel 2008), yet it remains a difficult choice of what metric(s) to use between species-specific approaches that require copious data to parameterize models and more general ones that capture general alterations to natural landscapes (Kupfer et al. 2006).

In addition to general purpose metrics, specific composite indices have been developed to characterize the effects of human activities, such as maps of "wildness" (Lesslie et al. 1988; Kliskey 1998; Aplet et al. 2000) or the human footprint (Hannah et al. 1995; Sanderson et al. 2002; Leu et al. 2008; Woolmer et al. 2008). Typically, these efforts combined mapped attributes on human population density, land cover, roads, and utility infrastructure, and these maps have found broad application in conservation and land planning. However, caution regarding composite indices has been advised (Schultz 2001; Hajkowicz and Collins 2007) because they can be difficult to interpret if the score has no direct physical basis, the conversion of raw values (e.g., people/ha) to classes likely violates the additivity axiom (i.e. a difference between 1 and 2 is the same as between 2 and 3), or if individual factors that are combined through addition exhibit colinearity.

In this paper I develop a parsimonious, cross-scale landscape metric to estimate the "naturalness" of a landscape—or conversely, the proportion of landscapes that are human-dominated. "Natural" landscapes are characterized by a high proportion of natural land cover types (i.e. forest, grassland, wetlands), as opposed to human-dominated types (i.e. urban/built-up, agricultural, roads). It builds on work that evaluated temporal changes in forest fragmentation (Wickham et al. 2008; Riitters et al. 2009a, b). The analysis is applied to data on land cover modifications including presence of roads, human activities associated with developed land use, housing density, roads, and road use (traffic), as well as incorporating how the broader landscape context modifies local conditions. The selection of these surrogate variables is supported by Woolmer et al.'s (2008) finding that the three most important variables of impact were land use/cover, human settlement, and roads.

I apply this metric to characterize the dynamics of "natural" landscapes across the US for recent (1992), current (2001), and near-term (2030) conditions. I summarize NL scores by levels of administrative protection, by major natural land cover types, and for four case-study national parks to illustrate its potential use by land managers and conservation practitioners.

Methods

Measuring landscape pattern

Proportion of a landscape occupied by a land cover type P is one of the best general measures of landscape pattern (Gardner et al. 1987; Turner 2005). P is the primary component of landscape composition and is correlated with measures of fragmentation (Neel et al. 2004; Gardner and Urban 2007), especially with higher ($P > 0.5$) values. Wickham et al. (2008) considered P to be fundamental because no other metric can be interpreted independently of it. Moreover, calculating P does not rely on first defining patch boundaries, which can be problematic (e.g., Fortin et al. 2000; Theobald and Hobbs 2002; McGarigal et al. 2009). This is particularly the case for landscapes with broad extents (e.g., states, ecoregions, continents), for naturally heterogeneous systems that are better represented as a gradient of conditions (Kupfer et al. 2006), and for general (non-species specific) approaches. Finally, P provides the basis for an unambiguous interpretation of loss or gain of a land cover type that is needed to assess landscape change (Wickham et al. 2008; Riitters et al. 2009a, b).

A number of landscape assessments have used P as the basis of an indicator of pattern and change. Riitters et al. (2002) computed P using three different neighborhoods to examine patterns of forest fragmentation across the US. Similarly the *Pattern of Natural Landscapes* metric was calculated using P with a single, moving window of 240 acres (Heinz Center 2008). Wickham et al. (2008) examined changes in forested landscape patterns from 1992 to 2001 with P and found overall declines in the proportion of forest over time, with lower forest density at larger window sizes. Riitters et al. (2009a, b) used proportion of developed, agricultural, and natural to estimate the landscape mosaic.

Two limitations remain when using P to characterize landscape pattern. First, landscape change often exhibits critical thresholds (Gardner and Urban 2007) and larger patches are often assigned higher conservation value than smaller patches. Consequently, metrics should be sensitive to patch size, such as the largest patch (Gardner et al. 1987), weighted mean patch size (Li and Archer 1997), or the effective mesh size m_{eff} (Jaeger 2000; Girvetz et al. 2008). Although these metrics are more sensitive to non-linear thresholds than P, they require an a priori definition of patches. A second limitation is that multi-scale application of P is typically computed and reported for each individual neighborhood only. Combining P values computed at multiple scales provides an integrated metric that represents multiple scales simultaneously (Gaucherel 2007; Zurlini et al. 2007; Wade et al. 2009).

Natural landscape metric

The NL metric overcomes the limitations to P in the following ways. First, the proportion of natural cover I at a location (i.e. a raster cell) can be loosely interpreted as the probability p that it is natural, so the likelihood that a given cell p_c will be influenced by one of its neighboring cells i is the product of the proportions ($p_c p_i$):

$$I_j = \sum_{i}^{n} p_i p_c / n$$

where p_c and p_i are the proportions of a land cover class in the center and neighboring cells (eight neighbors), at resolution or level j. This follows Jaeger's (2000) interpretation of m_{eff} approximating the joint probability of use between two adjacent patches, as well as Zurlini et al.'s (2007) probability that a disturbed pixel is adjacent to a disturbed pixel. Note that the center cell c is included in the neighborhood of i to n cells, so $n = 9$. As a simple illustration of the difference between the simple mean value in a neighborhood and I consider a 3×3 neighborhood containing values of 0.9. The standard approach would result in $P = 0.9$ while $I = 0.811$. If the center cell was replaced with a value of 0.2, then $P = 0.822$ while $I = 0.164$.

Second, integration across scales is accomplished by computing I at each scale for $j = \mathrm{k}$ circular neighborhoods (Fig. 1). For this analysis the resolution at $j = 1$ is set to 270 m and I used a logarithmic progression of neighborhood sizes (after Riitters et al. 2002): 0.07, 0.58, 5.90, 51.7, 478, 4186, and 38972 km^2. The precise number of scales (here $k = 7$) is less important than having a range of scales, in this case incorporating locations out to 109 km. Note also that the 270 m cells accurately represent the proportions computed from the 30 m resolution, because they were aggregated using the mean value.

Once I_j is computed for each neighborhood, a multi-scale metric is computed. One approach to combining values across a range of scales is to use multi-dimensional clustering techniques to identify homogenous zones (Zurlini et al. 2007; Wade et al. 2009), but this results in classed zones that can be challenging to relate to real world features (Zaccarelli et al. 2008). Instead, here I calculate the simple arithmetic mean across all scales at the finest resolution ($j = 1$,270 m), which is called the natural landscape (NL) metric:

$$NL = \sum_{j=1}^{k} I_j / k$$

This provides a computationally efficient way to incorporate both local and broad-scale structure into a comprehensive metric whose values rise monotonically from 0.0 to 1.0 with decreasing human modification. It also reflects the assumption that nearby disturbances have more of an impact than far away disturbances, but computing the mean value does not

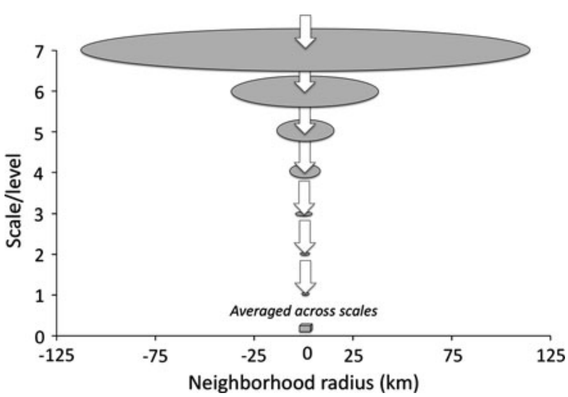

Fig. 1 Generating the natural landscapes (NL) metric starts with calculating the proportion of natural cover (I) for seven scales using circular neighborhoods of 0.07, 0.58, 5.90, 51.7, 478, 4186, and 38972 km^2. NL is then calculated by finding the mean value across all scales for each 270 m cell

allow one to examine how I changes as a function of scale (this would require examining I at different scales j). Because NL integrates the proportion of naturalness at multiple scales, it characterizes both compositional and structural aspects of the landscape (Zurlini et al. 2007). Note that because the neighborhoods overlap rather than being incremental, the effective weighting at each scale j (fine to coarse) declines with distance.

Landscape dynamics

I examined the landscape dynamics of the conterminous US by calculating NL on four models at three points in time: 1992, 2001, and 2030. To develop a national indicator of landscape change, I used data from the Multi-Resolution Land Characteristics Consortium's National Land Cover Dataset Retrofit Land Cover Change Product (NLCDr; www.mrlc.gov/changeproduct.php). This product was developed using a consistent processing method specifically designed to capture land cover changes between 1992 and 2001. The major NLCDr cover types were assigned a value of 1 for each 30 m pixel of "natural" cover types and a value of 0 to "human-dominated" types (Table 1). Note that land uses such as grazing that modify land cover condition but do not result in cover conversion are particularly difficult to account for in this approach. Also note that in the NLCDr most major roads (interstates, highways) are classified as urban/built-up as an artifact of the classification process related to impervious surface calculations. These artifacts are particularly problematic in rural areas, so I reprocessed the NLCDr data to replace cells classified as urban/built-up with adjacent natural land cover types. As a result, the proportion of urban/built-up cover was reduced from 5.11 to 2.69% of the US. Note that most secondary and local roads in rural areas tend not to be classified as urban/built-up in the raw NLCDr data. I refer to this as landscape model 1 (M_1). The progression of increasing data is illustrated in Fig. 2.

Land cover modifications associated with low-density residential housing (<1 unit/ha) were not captured in the urban/built-up class of NLCDr (Theobald 2005; Irwin and Bockstael 2007) but have important and widespread effects on habitat and ecological processes (Theobald et al. 1997; Hansen et al. 2005; Merenlender et al. 2009). As a result, I computed a second model (M_2) by finding the minimum value between the value of the proportion of natural land cover (I_1) from M_1 and amount of human modification of habitat caused by residential development. Commonly, the extent of human modification is estimated as a 100 m radius buffer around each housing unit (Theobald et al. 1997; Gonzalez-Abraham et al. 2007), but here I used empirical estimates of the "footprint" of land cover modifications visible from aerial photography around each housing unit (Leinwand 2009): 4.65, 2.65, and 0.33 ha per unit for rural (<1 unit per 16 ha), exurban (1 unit per 1–16 ha), and suburban/urban (>1 unit per 1 ha) densities. To calculate NL for 1992, I adjusted the NLCDr values by the human modification associated with housing density for 1990. Similarly, I adjusted the 2001 NLCDr using housing density for 2000. To approximate future conditions, I used housing density calculated on refined US Census blocks for 1990 and 2000 and forecasted density 2030 with NLCDr for 2001 (see Theobald 2005 and USEPA 2009 for detailed methods). I assumed other land cover types remained static from 2001 to 2030. Note that the incremental models reflect the conservative assumption that the degree of naturalness is the minimum value of any one model, not the cumulative effect of multiple datasets/models. This also reduces difficulties in interpreting NL due to potential co-linearities between data layers (Schultz 2001).

The third model (M_3) reflects further likely reductions in naturalness from M_2 due to the presence of highways, secondary, and local roads as mapped in the Streetmap 2006 database (Environmental Systems Research Institute (ESRI) 2007). I estimated the proportion of a 30 m cell that was directly impacted by the existence of a road, by measuring from aerial photography the width of the road and its immediately adjacent, visibly disturbed areas (e.g., the "shoulder" of a road). This estimate varied by road types (from Streetmap): interstates and state highways 100%; secondary roads 50%; local roads 30%; 4WD roads 10%. Note this is a more conservative estimate of area affected than other "footprint" estimates (e.g., Stoms 2000; Sanderson et al. 2002; Theobald 2003) because it explicitly excludes adjacent disturbance affects associated with road use.

Because incorporating the effects of road use, not just presence, is important (Forman and Alexander 1998; Chruszcz et al. 2003; Alexander et al. 2005),

Table 1 Assignment of natural/human-dominated values for each National Land Cover Dataset (retrofit) class

Class	Anderson Level I Code	Natural/Human-dominated
Water	1	No data
Urban/built-up	2	0
Barren	3	No data
Forest	4	1
Grassland/shrubland	5	1
Agricultural (cropland)	6	0
Wetlands/riparian	7	1
Snow/ice	8	1

The land cover types water (rivers, lakes, and reservoirs, oceans) and barren (which can be both natural rock/talus in alpine tundra areas or human-modified areas)—and were coded as "no data" to exclude them from the analysis, because there is ambiguity between reservoirs and lakes, and tundra and mining. Practically, many of the "natural" cover types can also include a variety of land uses that entail significant levels of management (e.g., rangelands)

Note that developed areas such as visitor areas, hotels, or campgrounds are not included in this analysis unless they are classified as urban in NLCDr, as housing density data were not measured on public land

I developed a fourth model (M_4) that included further reductions of naturalness from likely disturbance near highways from traffic (Jaeger et al. 2005). I used data on highway traffic volume measured by the annual average daily traffic (AADT; Table 2; USDOT 2007). AADT data were was available for 42% of the 176,000 highway segments nationwide. For 45% of remaining segments that did not have AADT values but did have a designated functional level (i.e. interstate, freeway, collector, local), I used the mean AADT for each level, calculated by state. For the remaining 13% of highway segments, I grouped segments using an attribute that differentiated urban from rural locations and then calculated the minimum AADT for each state for these two groups. I then applied a quadratic kernel density filter to generate a "smoothed" traffic volume raster, s, reflecting the assumption that the impact declines with distance out to 1 km away from a road (based on Forman and Alexander 1998). The impact (or proportion of loss) from highway use r was computed as a non-linear function of the smoothed AADT values:

$$r = \min\left(\sqrt{s} * 0.01,\ 1.0\right).$$

For example, the impact r for a cell on a highway with AADT $\geq$ 10,000 is 1.0, while an AADT of 5,000 is 0.71 and AADT of 100 is 0.1. For a cell that is 1 km or more from a highway, regardless of its use level, $r = 0.0$. Although the form of distance-decay and level of impact is subjective, it is based on general findings from road ecology on the distance-decay effects from vegetation modifications, additions of materials and chemicals (e.g., salt), changes to hydrology, generation of noise and light, and habitat collisions (Forman et al. 2003, p. 308). I also incorporated habitat loss due to the presence of active railways, t, by assuming the impact was 0.5 on 270 m cells that intersect railways and declined to 0.0 at a distance of 1 km—because data on rail traffic were not available, this estimates only the effect of railway presence.

To illustrate how NL values can provide contextual information for land managers, I summarized NL values by US GAP status codes (Scott et al. 2001) from the PAD-US v1 (Conservation Biology Institute 2009), for four case-study national parks representing natural to human-modified landscape contexts (Yosemite, Rocky Mountain, Yellowstone, and Delaware Water Gap), and by natural land cover types. I also compared maps of the NL values to the human footprint map (Sanderson et al. 2002), by inverting the human footprint scores and then normalizing the values to range from 0 to 1.0. The HF dataset was re-projected using bilinear interpolation to be consistent with the NL raster data.

Results

Natural landscapes vary across the US (Fig. 3) and are generally consistent with other national maps of protected lands that show that the western US is more

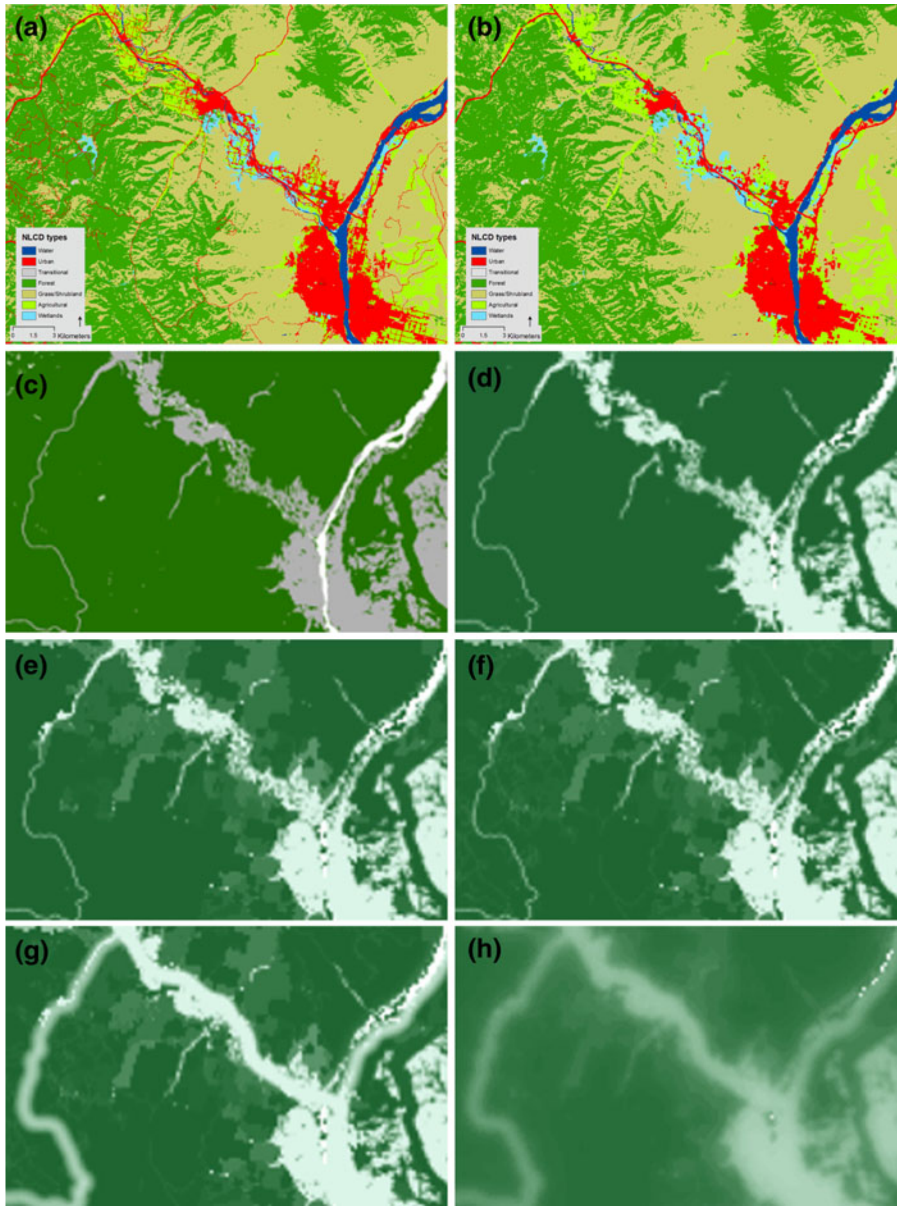

Fig. 2 An illustration of the data incorporated into the natural landscapes metric for the area around Wenatchee, Washington. **a** Original land cover from the 30 m NLCD retrofit land cover; and **b** land cover with secondary roads removed. **c** Refined land cover data are then converted to human-dominated (*grey*) and natural (*green*) classes. **d** The binary 0/1 data are up-scaled from 30 to 270 m using the mean proportion. Data on additional human modifications are added, including: **e** housing density; **f** the proportion of minor roads; and **g** highway traffic

natural, while the Midwest and East are more highly modified. On closer inspection, many additional subtle patterns emerge—many small pockets of "natural" areas are evident throughout, such as the Sand Hills of Nebraska, the Adirondack Mountains in New York, central Florida, and northern Maine. For the more than 8 million km^2 in the conterminous US, the national NL value ranged from 0.72161 to 0.66210 for M_1 and M_4 in 2001 (Table 3). This roughly corresponds to over 2.2–2.6 million km^2 that have been converted to human cover types and are no longer considered "natural". The top 1% of NL values in the US occur in central Idaho, Yellowstone National Park (WY), southeastern Utah, northwestern Arizona, southwestern New Mexico, southeastern Oregon, central Nevada, and Owens Valley (CA).

Including housing density information in addition to land cover types (M_2) causes the estimated loss of natural lands to increase by an additional 358,800 km^2 (Table 4), while including roads (M_3) further reduced natural lands 27,900 km^2 and highway traffic (M_4) yet another 94,100 km^2. The loss of

Table 2 Traffic volume and estimated road effect for different urban and rural functional road classes for the United States (USDOT 2007)

Urban road type[d]	Segments[a]	Length (km)	AADT[b]		Road effect[c]	
			Mean	St. Dev.	Mean	Minimum
Interstate	20,198	22,057	93,610	64,770	1.00	0.29
Freeway	7,179	15,999	66,430	56,971	1.00	0.28
Principal arterial	16,871	94,964	24,015	16,708	1.00	0.10
Minor arterial	932	3,820	15,389	9,746	1.00	0.23
Collector	404	385	9,947	10,576	1.00	0.13
Local	138	92	4,556	5,828	0.68	0.04
Rural road type						
Interstate	12,098	52,896	28,910	21,435	1.00	0.39
Freeway	14,569	164,004	10,938	11,189	1.00	0.09
Principal arterial	707	231,915	8,794	8,047	0.94	0.14
Minor arterial	173	1,366	6,366	5,206	0.80	0.16
Collector	13	65	1,517	1,403	0.39	0.08
Local	12	18	1,539	1,663	0.39	0.18

[a] The 2007 US National Atlas of Transportation contained a total of 176,000 segments—27,000 had no designated functional class information

[b] Annual average daily traffic

[c] Road effect ranged from 0.0 to 1.0 and was estimated as the square-root of AADT (with a maximum value of 1.0)

[d] Arterials provide a high level of mobility, while local roads emphasize high level of access—collectors are a compromise between mobility and access

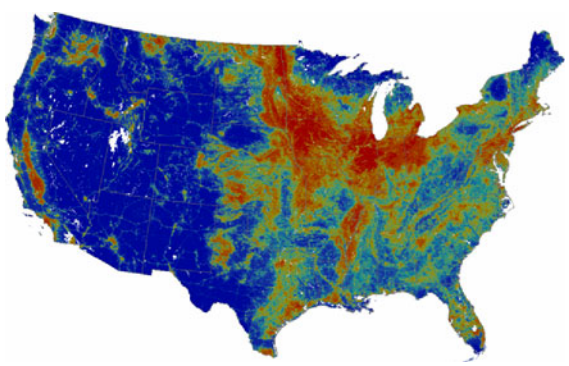

Fig. 3 The pattern of natural landscapes in 1992 (M_4) for the coterminous US using the natural landscapes metric. Much of the western US and northern Minnesota, Wisconsin, and Maine are dominated by "natural" landscapes (high NL values) that are shown in blue. Areas dominated by urban and/or cropland agriculture appear as highly modified areas, shown in *red*

naturalness due to landscape change observable in the NLCDr data from 1992 to 2001 (M_1) is estimated to be 13,600 km^2. Including housing density (M_2), roads (M_3), and traffic (M_4) results in an additional 87,500 km^2, 87,400 km^2, and 80,700 km^2 of natural lands lost. Using forecasted housing density for 2030, future development will likely cause an additional reduction of 82,100–92,200 km^2.

The NL value (M_4) averaged over protected lands with GAP status 1 (highest), 2, and 3 (lowest) in 2001 was 0.948 (SD = 0.099), 0.890 (SD = 0.161), and 0.924 (SD = 0.114). Roughly 1.4% of GAP 1, 4.6% of GAP 2, and 1.9% of GAP lands had NL values less than 0.5. The mean NL value (M_4) in 2001 for four national parks (Delaware Water Gap, Rocky Mountain, Yellowstone, and Yosemite) is: 0.66312, 0.93780, 0.97939, and 0.97106, respectively. Fine-scale variation can be seen as well (Fig. 4), such as the highways that cross through parks. Landscape change surrounding a park is readily quantified over time with NL in anticipation of residential growth in nearby areas. Park and ecoregional scores for M_4 can be compared to understand the immediate ecological context: e.g., Rocky Mountain's score is about 0.02–0.03 above its ecoregion and declining over time: 0.94021, 0.93780, and 0.92856 (for 1992, 2001, 2030). But the decline in ecoregional NL value (0.0075) is roughly three times the decline for the park from 1992 to 2001.

Table 3 Mean values for the Natural Landscapes metric computed on data that represent "naturalness" as a function of NLCD retrofit land cover data (M_1), residential housing density (M_2), road footprint (M_3), and highway traffic effects (M_4)

Year	Model			
	M_1 = land cover (NLCDr)	$M_2 = M_1$ and housing density	$M_3 = M_2$ and roads[a]	$M_4 = M_3$ and highway traffic[a]
1992	0.72329	0.68804	0.68456	0.67209
	(0.30146)	(0.30446)	(0.30209)	(0.30360)
2001	0.72161	0.67720	0.67374	0.66210
	(0.30196)	(0.30758)	(0.30522)	(0.30661)
2030	–	0.66579	0.66250	0.65193
		(0.31315)	(0.31083)	(0.31176)

Standard deviation is shown in parentheses

[a] Current (2001–2007) data were used for historical and future time periods

Table 4 Changes in the natural landscapes metric values as a function of including additional data (as represented by scenarios 1 to 4) and between time periods 1992–2001

	M_1 = land cover (NLCDr)	$M_2 = M_1$ and housing density	$M_3 = M_2$ and roads	$M_4 = M_3$ and highway traffic
1992–2001	−0.00169	−0.01084	−0.01082	−0.00999
	−13,653	−87,576	−87,406	−80,760
2001–2030	–	−0.01141	−0.01124	−0.01016
	–	−92,196	−90,836	−82,120
		M_1 to M_2	M_2 to M_3	M_3 to M_4
2001		−0.04440	−0.00346	−0.01165
		−358,781	−27,958	−94,123

The estimates of loss are computed in terms of proportion of US and area (km^2) of natural landscapes

Overall, the general patterns of modification shown by the human footprint (HF) and NL maps were roughly consistent at a coarse grain: the mean value of HF (converted to "naturalness") in the conterminous US in 2000 was 0.7603, as compared to NL = 0.6621 (M_4). The spatial distribution of the ratio of NL to HF, however, shows a couple of important differences at a finer grain (Fig. 5). Compared to the NL map, the HF estimated a higher impact along major interstate travel corridors and county highways, particularly in the western US, as well as around relatively isolated urban areas. This is likely due to the high estimated high impact score (~80%) assigned to areas 0–2 km and moderate impacts (~40%) 2–15 km from major roadways. For example, the mean HF score for RMNP was essentially the same as the US average (0.764). HF estimated a lower impact in exurban and rural residential areas, as well as in agricultural areas dominated by croplands—particularly in the midwest because of the HF assumed an impact score of 0.3–0.8 for croplands, whereas NL assume a 1.0 impact (naturalness value of 0.0).

Table 5 summarizes NL values by major "natural" land cover types from NLCD 2001. Wetlands are the most effected by human-dominated lands in 2001, with about 22% of their area within a human-dominated context, and 61% of wetlands are within at least low levels of human modification (<0.8). Roughly 15% of forested lands, 10% of grasslands, and 2% of shrublands are affected (<0.5) by human-dominated lands.

Discussion

Using the NL metric I estimated that in 2001 roughly one-quarter to one-third (M_1 = 27.9%, M_4 = 33.8%)

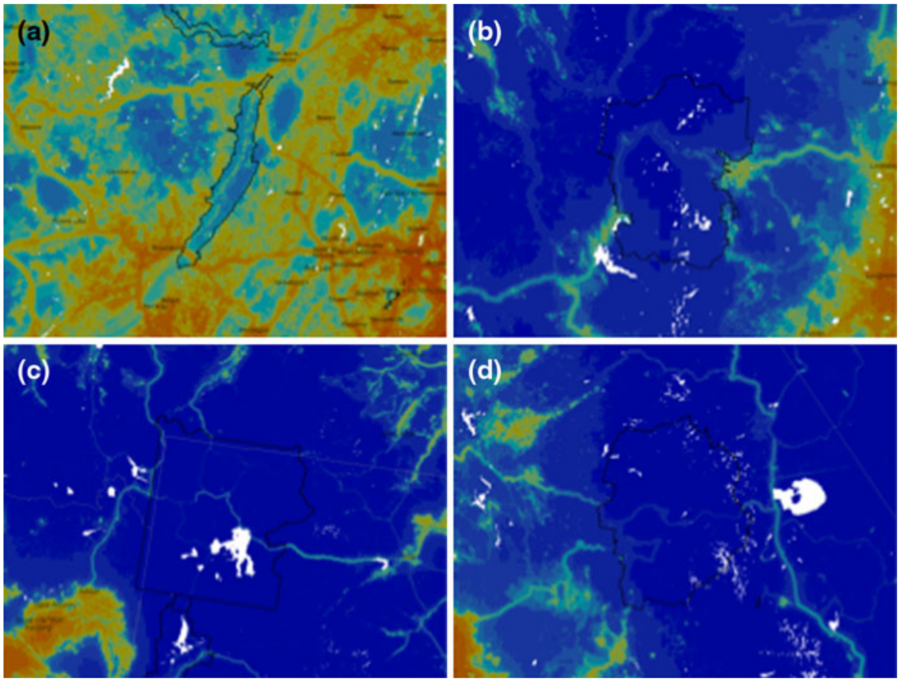

Fig. 4 NL maps in 2001 for four National Parks (clockwise from *top left*): Delaware Water Gap (eastern US), Rocky Mountain (CO), Yellowstone (MT, WY), and Yosemite (CA) National Parks. Park boundaries are shown with *black lines*. High NL values are depicted in *blue*, moderate values in *green*, and low values (highly modified landscapes) are in *red*. Locations with NO DATA are shown in *white*, which include water and barren cover types

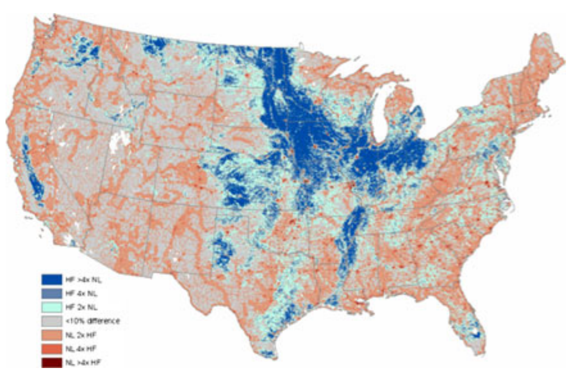

Fig. 5 A comparison of the ratio of values for the natural landscapes (NL) metric and the Human Footprint (HF; Sanderson et al. 2002) values. Agricultural (cropland) areas show where HF has higher naturalness values than NL (*blue*). Places where the HF naturalness values are lower than NL occur at urban areas and near urban areas (exurban) shown in *red*

of the conterminous US was influenced by human-dominated landscapes in 2001 (Table 3), which is higher than the raw proportion (25.9%, calculated at 30 m) obtained from simply grouping human-dominated cover types (urban/built-up and agricultural) from the NLCDr. The 1.6% additional loss estimated by NL comes from measurement of the broader effects (spatial context) of the human-dominated types. Including information about effects on natural landscapes due to housing densities beyond urban areas contributes an additional 4.8% loss, and including the presence of roads constitutes an additional 0.4% loss and highway use adds another 1.3%. It is notable that although built-up land cover classes are relatively well estimated in the NLCDr data, relatively subtle land cover changes such as timber harvesting are not captured well in these data. For example, in the Pacific Northwest, much of the timber harvesting cover types were not identified (NatureServe 2009).

These findings and map products are relevant to conservation practitioners to measure the consequences of changes in land use policy. For example, rapid population growth and resource extraction in the West has spurred the Western Governors Association to identify key wildlife corridors and crucial wildlife habitats and to make that information available to inform federal, tribal, state and local

Table 5 A summary of major "natural" land cover types from NLCD 2001 showing the proportion of a cover type within a given Natural Landscape metric score presented as cumulative distribution values

NLCD cover	Area (M km^2)	Natural landscape metric							
		<0.05	<0.1	<0.2	<0.5	<0.8	<0.9	<0.95	<1.0
Barren	0.06	0.000	0.003	0.016	0.075	0.188	0.276	0.404	1.000
Forest	2.07	0.000	0.002	0.016	0.151	0.490	0.640	0.758	1.000
Shrubland	1.69	0.000	0.000	0.001	0.021	0.114	0.221	0.390	1.000
Grassland	1.17	0.000	0.002	0.010	0.103	0.390	0.579	0.749	1.000
Wetlands	0.38	0.000	0.003	0.030	0.217	0.609	0.810	0.921	1.000

Roughly 15.1% of forested, 2.1% of shrublands, 10.3% of grasslands, and 21.7% of wetlands are affected (NL < 0.5) by human-dominated lands

planning and decision making processes—called the Wildlife Corridor Initiative (WGA 2008). Maps of NL could potentially be used in a variety of ways, such as to provide a systematic indicator of landscape condition that is consistent across political and administrative jurisdictions to complement local (i.e. state, county) data and knowledge; help identify initial corridors until state wildlife action plans can be revised to specifically map wildlife movement; target areas that are currently natural but are likely to be threatened by future land use growth to prioritize protection activities; and inform local (i.e. county, land trust, etc.) land use planning by providing data that are comprehensive regionally but set within the local context (i.e. NL values normalized to administrative boundary). Similarly, federal and state public land agencies are challenged to understand the possible effects of surrounding landscape changes on their protected lands (e.g., the USDA Forest Service's Open Space Conservation Strategy). An advantage of the multi-scale approach is that it circumvents the need to delineate an explicit ecosystem boundary around a public protected area, avoiding possible concerns of public dominion extending onto private lands. It also provides a way to characterize land cover effects inside or adjacent to protected areas (Zaccarelli et al. 2008; Wade and Theobald 2010).

The NL metric is similar to other methods that evaluate the effect of humans on natural landscapes such as the human footprint in that it uses surrogate spatial data on land cover, population, and roads, as well as relying on heuristically derived estimates of human-dominated cover types. NL differs in that it is a simpler metric that has a direct physical interpretation related to proportion of natural cover at a location, examines the broader, landscape-scale pattern to differentiate the spatial context, and assumes that impacts decline continuously as a function of distance, rather than using abrupt "distance bands" or "buffers". NL also does not rely on pre-established critical scales and avoids the persistent problem of the arbitrariness of defining a patch. Consequently, it is likely that NL will be useful for general assessments of condition at national and ecoregional extents, and because it provides an unambiguous estimate of change it is useful for long-term monitoring of condition. As demonstrated, NL can be easily summarized for different planning or administrative units, and was computed using standard datasets that can be readily updated over time.

The analysis conducted using NL incorporates data on residential housing density that provides critical information on private land uses missing from typical land cover-based analyses, as well as allowing preliminary forecasts of the effects of land use change on ecological condition. Similarly, this study explicitly incorporates traffic data because effects on ecological processes are related to road use (i.e. traffic volume). I used conservative (low) interpolated estimates of traffic volume for highway segments with missing values, but clearly a more refined highway traffic and effects database is a high priority for future work.

Moreover, the specific models that represent different data inputs and assumptions of what activities are damaging enable differentiation of large, busy roads near urban areas from smaller and more isolated stretches of highways, as well as inclusion of the effects of low-density residential areas. Additional human activities such as utility corridors, oil and gas wells, and gravel mines (e.g., Leu et al. 2008; Woolmer et al. 2008) as well as recreation on public lands (Reed and Merenlender 2008; Theobald et al. 2010) would be likely candidates to include for additional refinements to mapping of human modification. These might usefully build on the landscape mosaic approach (Riitters et al. 2009a, b) to differentiate the source of modification such as urban, agricultural, recreation, or energy on natural landscapes. Also, incorporating temporally specific road data beyond simply using current data for ~2001 that includes types, density, and traffic volume would be useful to understand recent changes from 1992 as well as to examine the potential effects of forecasted land use change. As a result, the estimates of naturalness in 1992 are likely slightly low and for 2030 slightly high.

Although the specification of neighborhoods used in computing NL was subjective, there is broad support in the literature (e.g., Forman et al. 2003; Hansen et al. 2005) for a distance-decay effect from localized land cover changes. Here the choice of calculating the multi-scale metric was simply the arithmetic mean, but other integrating techniques (e.g. median, minimum, geometric mean) might have some utility for different applications. Re-classification of land cover types to "naturalness" could represent more of a continuous gradient of effects (e.g., $0 \rightarrow 1$). For example, to reflect the assumption that intensive agriculture represents a lower degree of human modification than urban/built-up, it could be assigned a value of 0.5 rather than 0.0.

Conclusions

Human activities have modified the natural landscapes of the US, resulting in roughly 1/3 of the conterminous US (2.6 million km^2) in 1992 being classified as human-dominated. By 2001 this expanded by 80,800 km^2, and forecasted residential growth by 2030 will potentially lead to an additional loss of 82,100 km^2. The natural landscapes metric developed here provides a simple, robust measure landscape of dynamics that has a direct physical interpretation related to proportion of natural habitat affected at a location, represents landscapes as a gradient of conditions rather than as simply patch or matrix, and measures the spatial context of natural areas. Attention to the quality and extent of data that represents likely modification to natural habitats is important. The results provided here show that change between 1992 and 2001 can differ up to sixfold, depending on the types of data incorporated. The fine-grained maps provide a rigorous means of quantifying landscape dynamics that can inform conservation planning and long-term monitoring of natural resources at national, regional, and local scales.

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References

Alexander SM, Waters NM, Paquet PC (2005) Traffic volume and highway permeability for a mammalian community in the Canadian Rocky Mountains. Can Geogr 49(4): 321–331

Aplet G, Thomson J, Wilbert M (2000) Indicators of wildness: using attributes of the land to assess the context of wilderness. In: McCool SF, Cole DN, Borrie WT, O'Loughlin J (2000) Wilderness science in a time of change conference—Volume 2: wilderness within the context of larger systems; 1999 May 23–27; Missoula, MT. Proceedings RMRS-P-15-VOL-2. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, pp 89–98

Bosworth D (2004) Four threats to the Nation's forest and grasslands. Idaho Environmental Forum, Boise, Idaho

Chruszcz B, Clevenger AP, Gunson KE, Gibeau ML (2003) Relationships among grizzly bears, highways, and habitat in the Banff-Bow Valley, Alberta, Canada. Can J Zool 81(8):1378–1391

Crooks KR, Sanjayan MA (eds) (2006) Connectivity conservation. Cambridge University Press, New York

Environmental Systems Research Institute (ESRI). 2007. GDT Streetmap 2006 database

Fancy SG, Gross JE, Carter SL (2008) Monitoring the condition of natural resources in US National Parks. Environ Monit Assess 151:161–174

Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR (2005) Global consequences of land use. Science 309:570–574. doi:10.1126/science.1111772

Forman RTT, Alexander LE (1998) Roads and their major ecological effects. Annu Rev Ecol Syst 29:207–231

Forman RTT, Sperling D, Bissonette JA, Clevenger AP, Cutshall CD, Dale VH, Fahrig L, France R, Goldman CR, Heanue K, Jones JA, Swanson FJ, Turrentine T, Winter

TC (2003) Road ecology: science and solutions. Island Press, Washington, DC
Fortin MJ, Olson RJ, Ferson S (2000) Issues related to the detection of boundaries. Landscape Ecol 15: 453–466
Gardner RH, Urban DL (2007) Neutral models for testing landscape hypotheses. Landscape Ecol 22:15–29
Gardner RH, Milne BT, Turner MG, O'Neill RV (1987) Neutral models for the analysis of broad-scale landscape pattern. Landscape Ecol 1:19–28
Gaucherel C (2007) Multiscale heterogeneity map and associated scaling profile for landscape analysis. Landsc Urban Plan 82:95–102
Girvetz EH, Thorne JH, Berry AM, Jaeger JAG (2008) Integration of landscape fragmentation analysis into regional planning: a statewide multi-scale case study from California, USA. Landsc Urban Plan 86:205–218
Gonzalez-Abraham CE, Radeloff VC, Hammer RB, Hawbaker TJ, Stewart SI, Clayton MK (2007) Patterns of houses and habitat loss from 1937 to 1999 in northern Wisconsin, USA. Ecol Appl 17(7):2011–2023
Gross JE, Goetz SJ, Cihlar J (2009) Application of remote sensing to parks and protected area monitoring: Introduction to the special issue. Remote Sensing Environ 113:1343–1345
Gustafson EJ (1998) Quantifying landscape spatial pattern: what is the state of the art? Ecosystems 1:143–156
Hajkowicz S, Collins K (2007) A review of multi-criteria analysis for water resource planning and management. Water Resour Manage 21(9):1553–1566
Hannah L, Carr JL, Lankerani A (1995) Human disturbance and natural habitat: a biome level analysis of a global data set. Biodivers Conserv 4:128–155
Hansen AJ, DeFries R (2007) Ecological mechanisms linking protected areas to surrounding lands. Ecol Appl 17: 974–988
Hansen AJ, Knight RL, Marzluff JM, Powell S, Brown K, Gude PH, Jones K (2005) Effects of exurban development on biodiversity: patterns, mechanisms, and research needs. Ecol Appl 15(6):1893–1905
Heinz Center (2008) The State of the Nation's Ecosystems 2008: measuring the land, waters, and living resources of the United States. Island Press, Washington, DC
Hilty JA, Lidicker WZ, Merenlender AM (2006) Corridor ecology: the science and practice of linking landscapes for biodiversity conservation. Island Press, Washington, DC
Irwin EG, Bockstael NE (2007) The evolution of urban sprawl: evidence of spatial heterogeneity and increasing land fragmentation. Proc Natl Acad Sci USA 104(52):20672–20677
Jaeger JAG (2000) Landscape division, splitting index, and effective mesh size: new measures of landscape fragmentation. Landscape Ecol 15(2):115–130
Jaeger JAG, Bowman J, Brennan J, Fahrig L, Bert D, Bouchard J, Charbonneau N, Frank K, Gruber B, von Toschanowitz KT (2005) Predicting when animal populations are at risk from roads: an interactive model of road avoidance behavior. Ecol Modell 185:329–348
Kindlmann P, Burel F (2008) Connectivity measures: a review. Landscape Ecol 23:879–890
Kliskey AD (1998) Linking the wilderness perception mapping concept to the recreation opportunity spectrum. Environ Manage 22(1):79–88
Kupfer JA, Malanson GP, Franklin SB (2006) Not seeing the ocean for the islands: the mediating influence of matrix-based processes on forest fragmentation effects. Glob Ecol Biogeogr 15:8–20
Leinwand I (2009) Land use patterns and trends in the Southern Rocky Mountains, US at the public-private interface. MS Thesis, Colorado State University
Lesslie RG, Mackey BG, Preece KM (1988) A computer-based method of wilderness evaluation. Environ Conserv 15(3):225–232
Leu M, Hanser SE, Knick ST (2008) The human footprint in the West: a large-scale analysis of anthropogenic impacts. Ecol Appl 18(5):1119–1139
Li BL, Archer S (1997) Weighted mean patch size: a robust index for quantifying landscape structure. Ecol Modell 102:353–361
McGarigal K, Tagil S, Cushman SA (2009) Surface metrics: an alternative to patch metrics for the quantification of landscape structure. Landscape Ecol 24:433–450
Merenlender AM, Reed SE, Heise KL (2009) Exurban development influences woodland bird composition. Landsc Urban Plan 92:255–263
NatureServe 2009. Terrestrial ecological systems of the United States. http://www.natureserve.org/getData/USecologyData.jsp
Neel MC, McGarigal K, Cushman SA (2004) Behavior of class-level landscape metrics across gradients of class aggregation and area. Landscape Ecol 19:435–455
Noss RF (1990) Indicators for monitoring biodiversity: a hierarchical approach. Conserv Biol 4(4):355–364
Reed SE, Merenlender AM (2008) Quiet, non-consumptive recreation reduces protected area effectiveness. Conserv Lett 1:146–154
Riitters KH, Wickham JD, O'Neill RV, Jones KB, Smith ER, Coulston JW, Wade TG, Smith JH (2002) Fragmentation of continental United States forests. Ecosystems 5: 815–822
Riitters KH, Wickham JD, Wade TG (2009a) An indicator of forest dynamics using a shifting landscape mosaic. Ecol Indic 9(1):107–117
Riitters KH, Wickham JD, Wade TG (2009b) Evaluating anthropogenic risk of grassland and forest habitat degradation using land-cover data. Landsc Online 13:1–14
Sanderson EW, Jaiteh M, Levy MA, Redford KH (2002) The human footprint and the last of the wild. Bioscience 52(10):891–904
Schultz MT (2001) A critique of EPA's index of watershed indicators. J Environ Manage 62:429–442
Scott JM, Davis FW, McGhie G, Groves C (2001) Nature reserves: do they capture the full range of America's biological diversity? Ecol Appl 11:999–1004
Stoms DM (2000) GAP management status and regional indicators of threats to biodiversity. Landscape Ecol 15:21–33
Svancara LK, Scott JM, Loveland TR, Pidgorna AB (2009) Assessing the landscape context and conversion risk of protected areas using satellite data products. Remote Sensing Environ 113:1357–1369

Theobald DM (2003) Targeting conservation action through assessment of protection and exurban threats. Conserv Biol 17(6):1624–1637

Theobald DM (2005) Landscape patterns of exurban growth in the USA from 1980 to 2020. Ecol Soc 10(1):32

Theobald DM, Hobbs NT (2002) Functional definition of landscape structure using a gradient-based approach. In: Scott JM, Heglund PJ, Morrison ML, Haufler JB, Raphael MG, Wall WA, Samson FB (eds) Predicting species occurrences: issues of accuracy and scale, pp 667–674

Theobald DM, Miller JM, Hobbs NT (1997) Estimating the cumulative effects of development on wildlife habitat. Landsc Urban Plan 39(1):25–36

Theobald DM, Norman JB III, Newman P (2010) Estimating visitor use of protected areas by modeling accessibility: a case study in Rocky Mountain National Park, Colorado, USA. J Conserv Plan 6:1–20

Turner MG (2005) Landscape ecology: what is the state of the science? Annu Rev Ecol Evol Syst 36:319–344

US Department of Transportation (USDOT) (2007) National Transportation Atlas Database (NTAD) 2007 CD. Research and Innovative Technology Administration/ Bureau of Transportation Statistics, January 2007

U.S. Environmental Protection Agency (USEPA; Bierwagen B, Theobald DM, Pyke CR, Choate A, Groth P, Thomas JV, Morefield P) (2009) Land-use scenarios: national-scale housing-density scenarios consistent with climate change storylines. Global change research program, National Center for Environmental Assessment, Washington, DC; EPA/600/R-08/076F. http://www.epa.gov/ncea

US General Accounting Office (GAO) (1994) National Park Service: activities outside park borders have caused damage to resources and will likely cause more. US General Accounting Office, Washington, DC

Wade AA, Theobald DM (2010) Residential encroachment on U.S. protected areas. Conserv Biol 24(1):151–161

Wade TG, Wickham JD, Zacarelli N, Riitters KH (2009) A multi-scale method of mapping urban influence. Environ Modell Softw 24:1252–1256

Western Governors Association (WGA) (2008) Western Governors Association Wildlife Corridors Initiative Report. 29 June. http://www.westgov.org/wga/initiatives/corridors/index.htm Accessed 12 Oct 2008)

Wickham JD, Riitters KH, Wade TG, Homer C (2008) Temporal change in fragmentation of continental US forests. Landscape Ecol 23:891–898

Woolmer G, Trombulak SC, Ray JC, Doran PJ, Anderson MG, Baldwin RF, Morgan A, Sanderson EW (2008) Rescaling the human footprint: a tool for conservation planning at an ecoregional scale. Landsc Urban Plan 87:42–53

Zaccarelli N, Riitters KH, Petrosillo I, Zurlini G (2008) Indicating disturbance content and context for preserved areas. Ecol Indic 8:841–853

Zurlini G, Riitters KH, Zaccarelli N, Petrosillo N (2007) Patterns of disturbance at multiple scales in real and simulated landscapes. Landscape Ecol 22(4):705–721